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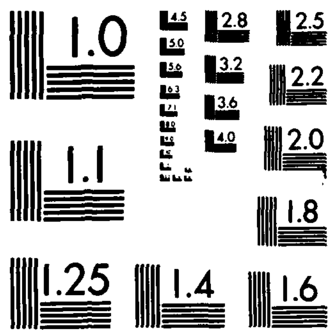

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Research in Geodesy Based Upon Radio Interferometric Observations of GPS Satellites

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31 December 1986

Final Report
5 February 1982-31 December 1985

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AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
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This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

DONALD H. ECKHARDT, Director
Earth Sciences Division

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Under Contract F19628-82-K-0002, MIT explored and extended the capabilities of the new technique of geodesy by radio interferometry using signals from the NAVSTAR Global Positioning System (GPS) satellites. Accuracy in the determination of long relative-position, or "baseline", vectors between fixed points on the earth was improved by the use of doubly differenced, dual frequency (L1 and L2 band), carrier phase observations, and by determining the orbits of the satellites from observations at widely spaced sites whose relative positions were well known a priori from quasar observations. Accuracy of about 1 part in 10^7 of the length of a long baseline, and 1 millimeter for a short baseline, was achieved.

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TABLE OF CONTENTS

1. Introduction

This is the final technical report submitted by the Massachusetts Institute of Technology (MIT) to the Geodesy and Gravity Branch of the Air Force Geophysics Laboratory (AFGL) under Contract F19628-82-K-0002, "RESEARCH IN GEODESY BASED UPON RADIO INTERFEROMETRIC OBSERVATIONS OF GPS SATELLITES". This report covers the entire period of performance of the contract, from February 5, 1982 through December 31, 1985.

The content of this report does not necessarily reflect the position or the policy of the U. S. Government, and no official endorsement should be inferred. Trade names are used herein only for purposes of identification and description, and no endorsement is implied.

1.1. Outline of this Report

An outline of this report is given in this subsection, §1.1.

The background of the contract is described with reference to work under preceding contracts in the following subsection, §1.2.

A chronological account of the performance of the present contract is presented, with references to publications, in §2. Note that some publications referenced in §2 were not supported at all by the present contract, but nonetheless contain useful and relevant information.

All publications wholly or partially supported by the contract are listed in §3. This list includes journal articles, short abstracts and full-length "Proceedings" publications of presentations at scientific meetings, two MIT Ph.D. theses, etc. This list also includes many publications, some of narrow interest or of a peripheral nature, not referenced in the chronology of §2. Details of research under the contract are best understood by reading the scientific reports listed in §3. Since over a thousand pages have been published and most of the publications are readily accessible, details are not reproduced here.

Contractor personnel who contributed to this project are listed in §4.

1.2. Background of the Contract

In December 1980 it was demonstrated that radio interferometric observations of NAVSTAR Global Positioning System (GPS) satellites could be used to determine a relative-position, or "baseline", vector between two points fixed on the earth's surface with centimeter-level accuracy in all vector components.[1,2] This demonstration was sponsored by the Geodesy and Gravity Branch of the Air Force Geophysics Laboratory under Contract F19628-80-C-0040.

The demonstration was performed with connected-element interferometers. In a connected-element interferometer, an antenna is located at each end of a baseline vector; both antennas simultaneously receive the signals transmitted by the satellites; the received signals are carried in real time by transmission lines from the separate antennas to a central location where the signal from one antenna is cross-correlated with the signal from the other antenna to generate interference "fringes". The fringes are then analyzed to determine the coordinate components of the baseline vector.

It is not practical to determine very long baselines with a connected-element interferometer; a satisfactory real-time connection between the ends of a long baseline is too expensive and/or inconvenient. The need for a real-time connection is eliminated in "Very Long Baseline Interferometry", or "VLBI", techniques[3] by recording on magnetic tape, locally, the signal received at each antenna. The tapes are then transported to a central location where the signals are played back and cross-correlated to generate the interference fringes.

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[1] Counselman III, C. C., and Gourevitch, S. A., "Miniature interferometer terminals for earth surveying: ambiguity and multipath with GPS," IEEE Transactions on Geoscience and Remote Sensing, vol. GE-19, pp. 244-252, 1981.

[2] Counselman III, C. C., Cappallo, R. J., Gourevitch, S. A., Greenspan, R. L., Herring, T. A., King, R. W., Rogers, A. E. E., Shapiro, I. I., Snyder, R. E., Steinbrecher, D. H., and Whitney, A. R., "Accuracy of relative positioning by interferometry with GPS: double-blind test results," Proc. Third Intl. Geodetic Symp. on Satellite Doppler Positioning, vol. 2, pp. 1173-1176, 1982.

[3] Rogers, A. E. E., Cappallo, R. J., Hinteregger, H. F., Levine, J. I., Nesman, E. F., Webber, J. C., Whitney, A. R., Clark, T. A., Ma, C., Ryan, J., Corey, B. E., Counselman, C. C., Herring, T. A., Shapiro, I. I., Knight, C. A., Shaffer, D. B., Vandenberg, N. R., Lacasse, R., Mauzy, R., Rayhrer, B., Schupler, B. R., and Pigg, J. C., "Very-long-baseline radio interferometry: the Mark III system for geodesy, astrometry, and aperture synthesis," Science, vol. 219, pp. 51-53, 1983.

VLBI is probably the most accurate of all known methods of determining a long relative-position vector. However, VLBI in its usual form is also an expensive and a cumbersome technique, involving the use of high gain antennas, wide bandwidth digital recorders, and extremely stable atomic clocks at the ends of the baseline; and wide-bandwidth synchronous digital tape reproduction and cross-correlation apparatus at the central processing location.

The possibility of doing "VLBI" with signals received from GPS satellites, but without high gain antennas, wide bandwidth recorders and cross-correlation apparatus, or atomic clocks, was suggested by the author and others in 1979.[4] An important aspect of this suggestion, related to the use of low gain antennas, was tested in the connected element interferometry demonstration mentioned above, in 1980.

A second aspect of the suggestion was the use of conventional GPS user equipment to separate the signals received by an upward-looking omni-directional antenna. (The suggested antenna was omni-directional in the sense that its pattern covered the whole sky; it was directional in the sense that it was upward-looking. That is, it rejected ground-reflected signals.) An omni-directional antenna receives a composite signal which includes components from all visible satellites. Since all GPS satellites transmit continuously on exactly the same frequencies, one satellite's signal tends to interfere with another's. To separate one satellite from another, conventional GPS user equipment correlates the composite signal with the unique, satellite-specific, code which modulates the signal transmitted by each GPS satellite. The use of such equipment to determine a relative position vector by interferometry was demonstrated in 1981, also under Contract F19628-80-C-0040.[5]

These two demonstrations set the stage for the present contract, under which MIT proposed research "to explore the capabilities and learn the limitations" of geodesy by interferometry with GPS. To perform this research, MIT would need interferometer terminals. Six terminals were purchased from the Steinbrecher Corporation of Woburn, MA, in 1983-84.

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[4] Counselman III, C. C., Cox, D. B., Greenspan, R. L., and Shapiro, I. I., "Backpack VLBI terminal with subcentimeter capability", in Radio Interferometry Techniques for Geodesy, NASA Conference Publication No. 2115, pp. 409-414, 1979.

[5] Greenspan, R. L., Ng, A. Y., Przyjemskyski, J. M., and Veale, J. D., "Accuracy of relative positioning by interferometry with reconstructed carrier GPS: experimental results," Proc. Third Intl. Geodetic Symp. on Satellite Doppler Positioning, vol. 2, pp. 1177-1196, 8 February 1982.

These "AFGL" terminals,[6] each including an upward-looking omni-directional antenna, a receiver, signal processing electronics, and a computer which controlled the terminal's operation and stored the data it acquired, were similar to the terminals known as MACROMETER● Interferometric Surveyors which Steinbrecher's subsidiary Macrometrics, Inc., had developed in 1981-82.[8]

The main difference between the AFGL terminals and MACROMETER terminals of the same vintage[9] is that an AFGL terminal observes the GPS signals in both the L1 (1575.42 MHz) and the L2 (1227.60 MHz) bands, whereas the MACROMETER terminals were single-band (L1 only). The dual-band capability of the AFGL units makes it possible to eliminate, virtually perfectly, ionospheric refraction effects on the observations. If not eliminated, such effects limit the accuracy of baseline determination to about 1 part in 10^6 (more or less, depending on the local solar time, etc.).

The AFGL terminals, like the MACROMETER terminals from which they were derived, differ from conventional GPS user equipment in that none of the GPS codes (the satellite-specific "C/A" and "P" codes which modulate the signals transmitted by the GPS satellites) is used in the AFGL terminals. This difference did not matter for our research. Equivalent observations may be – and have been – obtained with conventional GPS user equipment, such as the Texas Instruments model TI-4100, which uses the GPS codes.[10, 11]

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6 The AFGL terminals are also known by the name "MITES", standing for Miniature Interferometer Terminals for Earth Surveying, and introduced in a paper so entitled, by C. C. Counselman III and I. I. Shapiro, in Proc. 9th GEOP Conference (Dept. of Geodetic Science Rept. No. 280, Ohio State Univ., Columbus, Ohio 43210), pp. 65-85, October 1978.

●MACROMETER is a registered trademark of Aero Service Division, Western Geophysical Company of America, which purchased the Macrometrics business in 1984.

8 Counselman III, C. C., and Steinbrecher, D. H., "The MACROMETER™ compact radio interferometry terminal for geodesy with GPS," Proc. Third Intl. Geodetic Symp. on Satellite Doppler Positioning, vol. 2, pp. 1165-1172, 8 February 1982. This development was outside Government contracts.

9 A dual-band MACROMETER unit was introduced in 1985.

10 Ward, P., "An advanced NAVSTAR GPS geodetic receiver," Proc. Third Intl. Geodetic Symp. on Satellite Doppler Positioning, vol. 2, pp. 1123-1142, 8 February 1982.

11 Beutler, G., Gurtner, W., Rothacher, M., Schildknecht, T., and Bauersima, I., "Using the Global Positioning System (GPS) for High Precision Geodetic Surveys: Highlights and Problem Areas", IEEE PLANS '86 Position Location and Navigation Symposium Record, pages 243 - 250, published by the Institute of Electrical and Electronics Engineers, New York, 1986.

However, none of the conventional GPS user equipment which was available in 1983-84 was capable of the accuracy we required. Conventional GPS technology, using code correlation, was not mature.

For the research performed under this contract, the essential difference between the AFGL terminals and conventional GPS equipment was in the antennas. The AFGL terminal's antenna, developed originally by Donald H. Steinbrecher and Charles C. Counselman III [12] under Air Force Contract F19628-80-C-0040 and converted from single-band (L1 only) to dual-band (L1 and L2) under Contract No. 14-08-0001-19864 between MIT and the U. S. Dept. of the Interior (Geological Survey), has much less susceptibility to multipath interference, and a phase center which is much less variable.

2. Contract Performance

Under the present contract MIT explored and extended the capabilities of the new technique of geodesy by radio interferometry with GPS. Prior to the start of work under this contract it had been demonstrated that short baselines, with lengths of the order of 100 meters or less, could be determined by GPS interferometry with centimeter-level accuracy. Although one commercial GPS interferometry instrument had already been built[13] and another was under development,[14] it remained to be shown how accurately a much longer baseline, of tens or hundreds of kilometers, could be determined. On the other hand, it was correctly anticipated that for long baselines the chief problems would be (i) to eliminate differential effects of the ionosphere on the propagation of the satellite signals, and (ii) to determine the orbits of the satellites more accurately.

It was believed, although not universally accepted at the time, that errors due to differential ionospheric effects over long distances could be reduced below the centimeter level by combining observations of the signals simultaneously in two frequency bands. Thus, we had new, dual-band interferometer terminals built. As discussed in §1.2, these terminals used the only GPS positioning technology available at the time, an unconventional codeless technology, which had demonstrated centimeter-level accuracy over short distances.

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[12] For a detailed description see U. S. Patent No. 4,647,942, "CIRCULARLY POLARIZED ANTENNA FOR SATELLITE POSITIONING SYSTEMS," to be issued March 3, 1987.

[13] Counselman III, C. C., and Steinbrecher, D. H., op. cit.

[14] Ward, P., op. cit.

In order to improve the determination of the satellite orbits, the dual-band terminals were used to observe the satellites eventually from sites several thousand kilometers apart. However, the dual-band terminals were not available until the spring of 1983. While waiting for them, we made substantial progress using single-band terminals which the manufacturer, Steinbrecher Corporation (StC), loaned us.

In the spring of 1982, the borrowed terminals were used to measure baselines between geodetic monuments near the Haystack Observatory's 120-ft. radio telescope; its "Westford" 60-ft. telescope, 1.1 km away; and the transcontinental geodetic traverse station atop Mt. Wachusett, 36 km away.[15] Both baselines had been measured previously by the National Geodetic Survey (NGS) as part of a federal interagency campaign to validate radio-interferometric and laser-ranging geodetic measuring techniques.[16] The results of our GPS-based interferometric measurements were consistent with the NGS measurements within the uncertainty of the latter: 5 mm in each of three coordinates for the 1.1-km Haystack-Westford baseline, and under 5 cm in length and 1 arcsecond in azimuth for the 36-km Haystack-Wachusett line. (The NGS had not accurately measured the vertical component of this line.)[17,18]

In the summer of 1982 we left a terminal set up at the Haystack Observatory, and observed with it on seven days. We combined the data from these observations with data from a similar terminal which was operated in Woburn by StC, to determine the 30-km baseline between Haystack and Woburn.[19] The purpose of this series of observations was to study the effects of tropospheric and ionospheric variability, and of errors in

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[15] In these measurements MIT was assisted substantially by the manufacturer, who provided, in addition to the interferometer equipment, portable battery and gasoline power supplies, vehicles, radiotelephones, and engineers, technicians, and other personnel who were familiar with the equipment, having previously made several baseline measurements at and near their plant in Woburn, MA.

[16] Carter, W. E., et al., "Haystack-Westford Survey", NOAA Tech. Memo. NOS NGS 21, Sept. 1979, avail. from the National Geodetic Survey, Rockville, MD.

[17] Counselman III, C. C., "The Macrometer interferometric surveyor", in Symposium on Land Information at the Local Level, pp. 233-241, University of Maine, Orono, 1982.

[18] Counselman III, C. C., Abbot, R. I., Gourevitch, S. A., King, R. W., and Paradis, A. R., "Centimeter-level relative positioning with GPS," J. Surv. Eng. (ASCE), vol. 109, pp. 81-89, August 1983.

[19] Bock, Y., Abbot, R. I., Counselman, C. C., Gourevitch, S. A., King, R. W., and Paradis, A. R., "Geodetic accuracy of the Macrometer model V-1000," Bull. Géodésique, vol. 58, pp. 211-221, 1984.

the satellite ephemerides[20] which we received from the Naval Surface Weapons Center (NSWC). When we analyzed the data from each day separately, we obtained baseline-vector determinations which spread by about 20 cm in the worst vector component, and 12 cm in the baseline length. Ephemeris error appeared to be the dominant cause of the scatter, although ionospheric effects were also evident. No tropospheric effects could be discerned, despite major changes in the weather which occurred during the observation period.

In the summer of 1982 we also made substantial progress in the writing of the computer programs by which we would eventually improve the ephemerides of the GPS satellites.

By March 1983, StC had completed two dual-band terminals. We began using one of the two as a test bed for the development of dual-band interferometric data-processing software, while StC worked on various problems in the new dual-band electronics. We also tested our baseline-determining software for the first time with a very long baseline, by processing data from a 3600-km long baseline between two StC tracking stations.[21] The difference between separate determinations on consecutive days was 5 parts in 10^7 of the baseline length. Then, with data from additional days, we were able to determine the orbit of a GPS satellite. The resulting ephemeris differed from NSWC's ephemeris by about $2x10^{-6}$ radian of geocentric arc. The difference was due mainly to the effects of instabilities of the atomic-cesium-beam frequency standards that governed StC's receivers.

In April 1983, with the assistance of StC, Geo/Hydro, Inc., the NGS, NASA, Haystack Observatory, the National Radio Astronomy Observatory, and the Naval Research Laboratory, we obtained coordinated observations from a total of eight widely-spaced sites, including two sites with atomic-hydrogen-maser frequency standards, which were much more stable than the cesium standards. This experiment enabled NGS to determine differences between some of the coordinate systems used in GPS, satellite-Doppler, satellite-laser-ranging, and quasar-VLBI geodesy.[22] NGS was also able to compare Doppler and quasar-VLBI determinations of an

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[20] An *ephemeris* (plural, *ephemerides*) is a description, usually in the form of a numerical table, of the time-varying position of an orbiting body.

[21] The data were provided at no cost to the Government.

[22] Hothem, L.D., et al., "Analyses of Doppler, Satellite Laser, VLBI, and Terrestrial Coordinate Systems", presented by W.E. Carter at the XVIII General Assembly of the International Association of Geodesy, Symposium d, August 15-27, 1983.

approximately 845-km long baseline with our own GPS-interferometry determination. The difference between ours and the quasar-VLBI determination, which was probably more accurate, was about 5 parts in 10^7.

Other results from the April 1983 multi-site observations included a demonstration that all three vector components of a 748-m baseline could be determined accurately within 1 millimeter or less, and that the components of baselines 20 to 40 km long could be determined within 1 part in 10^6.

We completed hardware debugging and laboratory testing of the new dual-band terminals in the summer of 1983, using them to measure a very short baseline in Woburn. By November 1983, we had installed the terminals at two widely separated, hydrogen-maser-equipped, radio telescope sites: the Haystack Observatory in Massachusetts, and the Naval Observatory Timing Sub-Station (NOTSS) in Florida. Each terminal was connected by a modem to a telephone line so that we could control the observations and recover the data remotely, at MIT.

We made a similar installation at a third hydrogen-maser-equipped radio telescope site, the G. R. Agassiz Station (GRAS) of the Harvard College Observatory in Texas, in 1984. We analyzed observations from these and other sites on several days in 1984 in various ways in order to learn how best to determine the orbits of the GPS satellites. We concluded, in a paper presented at the April 1985 First International Symposium on Precise Positioning with the Global Positioning System,[23] that we were able to determine the orbits within a few parts in 10^7.

In other papers presented at that Symposium, we gave mathematical details of our method of processing GPS phase observables;[24] and one of us (Counselman) and co-authors from Aero Service and StC reported that with a dual-band interferometer system it was possible to determine a baseline within one part per million (1 ppm), given only 15 minutes of observing time.[25]

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23 Abbot, R. I., Bock, Y., Counselman III, C. C., King, R. W., Gourevitch, S. A., and Rosen, B. J., "Interferometric determination of GPS satellite orbits," Proc. First International Symposium on Precise Positioning with the Global Positioning System, vol. 1, pp. 63-72 (Avail. from the National Geodetic Information Center, NOAA, Rockville, MD 20852) April, 1985.

24 Bock, Y., Abbot, R. I., Counselman III, C. C., King, R. W., and Gourevitch, S. A., "Three-Dimensional Geodetic Control by Interferometry with GPS", ibid., vol. 1, pp. 63-72.

25 Ladd, J. W., Counselman III, C. C., and Gourevitch, S. A., "The MACROMETER II™ dual-band interferometric surveyor," ibid., vol. 1, pp. 175-180. This work was done outside the Contract.

In a tutorial paper published in the August 10, 1985 issue of the Journal of Geophysical Research, we described how we had used interferometry with GPS to establish a three-dimensional, 35-station, geodetic control network accurate at the 1-ppm level.[26]

A comprehensive tutorial on many aspects of geodesy by interferometry with GPS, both theoretical and practical, was co-authored by one of us (R. W. King, supported by this contract); E. G. Masters, C. Rizos, and A. Stolz of the Univ. of New South Wales (Australia, not supported by this contract); and J. Collins of Geo/Hydro, Inc. (also not supported by this contract) in 1985.[27]

In papers presented at the 1985 Fall Meeting of the American Geophysical Union, we reported repeated determinations of the GPS satellite orbits with uncertainties of 2 parts in 10^7 (0.2 ppm),[28] and repeated determinations of a 30-km baseline with r.m.s. scatters of 2-3 parts in 10^7 in all three coordinates.[29]

In March-April 1985 we participated in an experiment involving coordinated observations of the GPS satellites by about twenty organizations at sites distributed across the U. S.[30] For the most part, analyses of the data from this experiment have been performed outside the present contract. Several analyses of the observations made with the AFGL terminals have

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[26] Bock, Y., Abbot, R. I., Counselman III, C. C., Gourevitch, S. A., and King, R. W., "Establishment of three-dimensional geodetic control by interferometry with the Global Positioning System," J. Geophys. Res., vol. 90, pp. 7689-7703, August 10, 1985.

[27] King, R. W., Masters, E. G., Rizos, C., Stolz, A., and Collins, J., "Surveying with GPS", Monograph No. 9, School of Surveying, The University of New South Wales, Kensington, N.S.W., Australia, iv+128 pp., November 1985.

[28] Bock, Y., Abbot, R. I., Counselman III, C. C., and King, R. W., "Results of the March 1985 GPS High-Precision Baseline Test: Orbit Determination" (abstract), Eos Trans. AGU, vol. 66, p. 843, 1985.

[29] Gourevitch, S. A., Bock, Y., Abbot, R. I., Counselman III, C. C., King, R. W., and Ladd, J. W., "Repeated Determinations of a 30-km Baseline with Sub-Centimeter Scatters in Three Coordinates" (abstract), EOS Trans. AGU, vol. 66, p. 843, 1985.

[30] See the overview by Melbourne, et al., 1985, and the many other papers presented at the special session entitled "Results of the March 1985 GPS High-Precision Baseline Test" of the 1985 Fall Meeting of the AGU.

yielded determinations of the satellite orbits and of various baselines with accuracies of the order of 1 part in 10^7 or better.[31, 32, 33, 34, 35, 36]

3. Publications

In this Section all publications wholly or partially supported by the Contract are listed chronologically by year of publication, and for each year, alphabetically by author.

1982

Cappallo, R. J., King, R. W., Counselman III, C. C., and Shapiro, I. I., "Evidence for lunar librations near resonance", Celestial Mechanics, vol. 26, p. 145, 1982.

Counselman III, C. C., Cappallo, R. J., Gourevitch, S. A., Greenspan, R. L., Herring, T. A., King, R. W., Rogers, A. E. E., Shapiro, I. I., Snyder, R. E., Steinbrecher, D. H., and Whitney, A. R., "Accuracy of relative positioning by interferometry with GPS: double-blind test results", Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, vol. 2, pp. 1173-1176, 1982.

King, R. W., "Dissipation in the moon: a review of the experimental evidence and physical implications" (abstract), in IAU Colloquium on High-Precision Earth Rotation and Earth-Moon Dynamics, O. Calame, ed., D. Reidel, Dordrecht, 1982.

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[31] Abbot, R. I., et al., "GPS Orbit Determination", in Proceedings of the Fourth International Geodetic Symposium on Satellite Positioning, vol. 1, pp. 271-273, publ. by the Univ. of Texas, Austin, 1986.

[32] Abbot, R. I., et al., "Assessment of GPS Accuracy on a 250-km Baseline" (abstract), EOS Trans. AGU, vol. 67, p. 910, 1986.

[33] Davidson, J. M., et al., "Improved Application of the Fiducial Concept for GPS-Based Geodesy" (abstract), EOS Trans. AGU, vol. 67, p. 262, 1986.

[34] Davidson, J. M., et al., "Demonstration of the Fiducial Concept Using GPS Data from the March 1985 and November 1985 Field Tests", Proc. Fourth Intl. Geod. Symp. on Sat. Pos'g.

[35] Ware, R., et al., "Determination of the OVRO-Mojave During the Spring 1985 GPS Test", ibid.

[36] Beutler, G., et al., "Using the Global Positioning System (GPS) for High Precision Geodetic Surveys: Highlights and Problem Areas", in the IEEE PLANS '86 Position Location and Navigation Symposium Record, pages 243 - 250, 1986.

Morgan, P. J. and King, R. W., "The MIT lunar and planetary ephemeris", Proc. Fourth International Conference on Laser Ranging Instrumentation, University of Texas Publ. in Astronomy No. 19, pp. 239-274, 1982.

Morgan, P. J., King, R. W., and Shapiro, I. I., "Spectral analysis of variation of latitude derived from lunar laser ranging and satellite Doppler observations" (abstract), EOS Trans. AGU, vol. 63, p. 302, 1982.

1983

Abbot, R. I., Cefola, P., and Tse, S., "Satellite orbit theory for a small computer", Astrodynamics, vol. 54, part 1, pp. 543-572, 1983.

Bock, Y., "Estimating Crustal Deformations from a Combination of Baseline Measurements and Geophysical Models," Bulletin Géodésique, vol. 57-3, pp. 294-311, 1983.

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